Passive Dynamic Stability of a Hovering Fruit Fly: a Comparison between Linear and Nonlinear Methods*

Na GAO** and Hao LIU**
** Graduate School of Engineering, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan
E-mail: hliu@faculty.chiba-u.jp

Abstract
Insects exhibit exquisite control of their flapping flight, capable of performing precise stability and steering maneuverability. To tackle this highly nonlinear problem we have developed two simulation-based methods to investigate the dynamic passive stability of insect flight: linear and nonlinear methods. In the linear theory, the equations of body motion are linearized and the techniques of eigenvalue and eigenvector analysis are employed to obtain the natural modes. Three natural modes are identified including an unstable oscillatory mode, a stable fast subsidence mode and a stable slow subsidence mode, which indicate that the fruit fly hovering flight is dynamic unstable. While in the nonlinear theory, the equations of 6 DoF motion are solved directly by coupling with the N-S equations. The time-varying time histories of the state variables are calculated, indicating that the state of fruit fly under disturbance conditions shows a very nonlinear transient interval initially but turns to unstable eventually. However, our results also illustrate that a fruit fly does have sufficient time to apply some active mediation to sustain a steady hovering before losing body attitudes.

Key words: Insect Flight, Fruit Fly, Passive Dynamic Stability, Flight Dynamics, NS Equation

1. Introduction
Flying insects, in general, perform excellent flight stability and maneuverability while steering and maneuvering by rapidly and continuously varying their wing kinematics (1-3), which are attractive interests to mimic in the development of micro air vehicles (MAVs) (4). Till now, studies on insect flight stability and maneuverability have been conducted mostly based on observation and experiments in terms of visually mediated response (5-8) and haltere mediated response (9-12). However, these studies nevertheless rest at the level of providing a control analysis isolating flight system motions from the forces that produce them. Without the link between forces and motions, it is impossible for this statistical approach to examine how the system will respond to external disturbances and what kind of wing-body kinematics will be employed in order to control the system. A challenging problem in uncovering the essential physics – such remarkable mechanisms in insect flight control is focused to answer a central question of how the wing-body kinematics, the inertial and aerodynamic forces, and the dynamics of body attitudes are interacted mutually in terms of Newtonian mechanics.

Insect flight dynamic stability was first analyzed by Taylor and Thomas (13) based on experimental data of aerodynamic forces and moments. By introducing an assumption that
an insect body can be approximated as a rigid body during flapping flights they solved the equations of 3DoF (degree of freedom) motion (hence, the longitudinal dynamic stability) to obtain a linear time-invariant (LTI) dynamic model. Sun and Xiong (14) and Gao et al. (15) used the same framework to model the flight dynamics of hovering bumblebee and hawk moth based on computational fluid dynamic modeling of hovering aerodynamics. Recently, in order to solve a problem of time-varying dynamics as is in insect flapping flight, Taylor and Żbikowski (16) developed a semi-empirical model of 3DoF flight dynamics of desert locusts to examine how the individual insect will respond to disturbances. They established a nonlinear time-periodic (NLTP) model to analyze the time course of longitudinal state variables, and suggested the dynamic instability of desert locust flight.

We here investigate the dynamic stability of hovering fruit fly by using both of the linear and nonlinear methods. In the linear study, the longitudinal disturbed motion is investigated and three natural modes are identified: one unstable oscillatory mode, one fast subsidence mode and one slow subsidence mode. As the disturbed motion is a linear combination of the three natural modes, the hovering fruit fly flight is identified to be unstable. In the nonlinear study, 6DoF equations of motion are loosely coupled with N-S equation. The time histories of state variables under longitudinal disturbance conditions are represented in which the divergences of the state variables also suggest dynamic unstable in longitudinal fruit fly hovering flight.

2. Computational model

2.1 A biology-inspired dynamic flight simulator

This study employs a biology-inspired, dynamic flight simulator (4, 17-19), which is very versatile, easily integrating the modeling of realistic wing-body morphology, realistic wing-body kinematics, and unsteady aerodynamics in insect flight. A morphological model is built based on an effective differential geometric method for reconstructing geometry of and a specific grid generator for the wings and body; and a multi-blocked, overset-grid method is utilized to deal with complex wing-body geometries and complicated flapping movements (23, 24). A kinematic model is constructed to be able to mimic the realistic wing-body kinematics of flapping flight; and an efficient analytical method combined with three coordinate systems is employed for the dynamic regridding: a wing base-fixed coordinate system o’x’y’z’ (Fig. 1a); a body-fixed coordinate system oxyz (Fig. 1b); and a global coordinate system OXYZ (Fig. 1b) (20). The wing-body kinematic model was constructed based on the measurement of hovering flight of a fruit fly with high-speed cameras (Fig. 1c) (21). Here we chose fruit fly as the research object not only because we have the exhaustive information of its morphologic and kinematic data, but also because of its excellent stability and maneuverability. The Reynolds number in hovering flight can be defined as $Re=cmU_{ref}/\nu$, here $\nu$ is the kinematic viscosity of air ($1.5\times10^{-5}$ m$^2$/s$^{-1}$). A fortified finite-volume method (FVM)-based NS solver for the dynamically moving system is developed and verified to be self-consistent by a variety of benchmark tests; and evaluation of flapping energetics is established on inertial and aerodynamic forces, torques and powers (4). Moreover, validation of this insect dynamic flight simulator is achieved by comparisons of aerodynamic force-production with measurements in terms of the time-varying and mean lift and drag forces. Results for four typical insect hovering flights (hawk moth, honeybee, fruit fly and thrips) over a wide range of Reynolds numbers from $O(10^3)$ to $O(10^4)$ demonstrate its feasibility in accurately modeling and quantitatively evaluating the unsteady aerodynamic mechanisms in insect flapping flight (17).
Figure 1. (a) Definition of 3D movement of a flapping wing: positional angle $\psi$ around the $x'$-axis; elevation angle $\theta$ around the $z'$-axis and feathering angle $\alpha$ around $y'$-axis. We assume a body angle $\chi$ of 45º and a stroke plane angle $\beta$ of 0º. (b) The local body-fixed coordinates $oxyz$ and the global earth-fixed coordinates $OXYZ$, in which $Z$-axis points to the opposite gravitational direction. Definitions of the aerodynamic force components $(F_x, F_y, F_z)$, aerodynamic moment components $(T_x, T_y, T_z)$ and the state variables $(u_b, v_b, w_b, \rho_b, q_b, \tau_b)$ under a body-fixed coordinates $oxyz$. The body-fixed coordinate is centered on the center of gravity with the $x$-axis being horizontal and pointing forward. Each of the vectors is signed positive in the direction shown. (c) Time variations of positional angle, elevation angle and feathering angle in constructing the wing-body kinematics.

2.2 Dynamic model
2.2.1 Equations of 6DoF motion

In the present study, a fruit fly model is treated as a bilaterally symmetric rigid body. The treatment of rigid body model leads not only to fix the center of gravity (C.G.) but also to maintain the moment of inertia of the body constant about the body-fixed stability coordinate system. This is reasonable since the fruit fly’s wings comprise less than 0.3% of the total mass of the insect. Then, a single rigid-body dynamic model can be constructed based on the Newton-Euler equations of 6DoF motion as a set of six coupled nonlinear ordinary differential equations, such as:

\[ \dot{u}_b = -q_b w_b + r_b v_b + g\sin\theta + \frac{F_x}{m}, \]  
\[ \dot{v}_b = p_b w_b - r_b u_b - g\cos\theta\sin\phi + \frac{F_y}{m}, \]  
\[ \dot{w}_b = -p_b v_b - q_b u_b + \frac{F_z}{m}. \]
\begin{align}
\dot{\omega}_b &= q_b u_b - p_b v_b - g \sin \theta \cos \phi + \frac{F_z}{m}, \\
\dot{p}_b &= \frac{(I_{zz} - I_{yy}) r_b q_b + T_z}{I_{xx}}, \\
\dot{q}_b &= \frac{(I_{xx} - I_{zz}) r_b p_b + T_y}{I_{yy}}, \\
\dot{r}_b &= \frac{(I_{yy} - I_{xx}) p_b q_b + T_z}{I_{zz}},
\end{align}

where \((X, Y, Z)\) denote the three aerodynamic forces acting along \(x-, y-\) and \(z\)-axes; \((L, M, N)\) the three aerodynamic torques (pitching, rolling and yawing) about three body axes; \((\theta, \phi)\) the pitch and roll angles; \((u_b, v_b, w_b)\) the three components of translational velocity of the body; \((p_b, q_b, r_b)\) the three components of angular velocity of the body; and \(I_x, I_y, I_z\) the moments of inertia about the body axes, respectively. Note that the translational and angular velocities of the body \((u_b, v_b, w_b, p_b, q_b, r_b)\) are defined as six state variables describing the 6DoF motion in the body-fixed coordinate system. Body mass \(m\), moments of inertia \(I_x, I_y, I_z\) and gravitational acceleration \(g = 9.8 \text{ m/s}^2\) are all assumed to be constant.

2.2.2 Linearized equations in longitudinal motion

In the linear theory, the equations of motion can be linearized by approximating the body’s motion as a series of small disturbance \((u_b, w_b)\) to be given in a range of -0.1~0.1 and \(q_b\) to be given in a range of -0.005~0.005) from a steady reference flight condition. Here we only investigate the longitudinal stability in which the linearized equations are as:

\[
\dot{x} = Ax
\]

Where the state vector \(x = [\delta u \delta w \delta q \delta \theta]^T\). The symbol \(\delta\) denotes a small disturbance quantity. The constant system matrix \(A\) is given by

\[
A = \begin{bmatrix}
X_u / m & X_v / m & X_q / m & g \\
Z_u / m & Z_v / m & Z_q / m & 0 \\
M_u / I_x & M_v / I_y & M_q / I_z & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\]

where \(X_u, X_v, X_q, Z_u, Z_v, Z_q, M_u, M_v, M_q\) and \(M_0\) are the aerodynamic derivatives. Using the technique of eigenvalue and eigenvector analysis, one can estimate the stability of system under a certain disturbance condition by the sign of the real part of the eigenvalue\(^{13}\). If the real part is positive, the system is dynamically unstable; if the real part is negative, the system is dynamically stable.

2.3 Coupling of the computational fluid dynamics (CFD) and dynamic models

Coupling of the CFD model and the dynamic model is achieved by solving the equations of 6DoF motion (Eq. (2.1)) based on the computation of CFD model. Here, with consideration of the passive dynamic flight (latency) that the insect does not carry out any active feedback controls we choose an effective mathematical method to represent the time-varying forces and moments by introducing Fourier series and embedding them into the Eq. (2.1). Note that a direct inner coupling of the CFD and dynamic models may be a straightforward method but it is, in general, difficult and time-consuming to realize an equilibrium flight with the non-tuning (unchanged) wing kinematics under some specific
Firstly, the time-varying aerodynamic forces and moments are computed based on the CFD model under one equilibrium condition and six one-directional disturbance conditions. In the computation, the same wing kinematics is used as no feedback is applied during latency. Time histories of the aerodynamic forces and moments under the equilibrium condition are computed over two complete wing beat cycles and the 6DoF disturbance conditions are added from the third cycle, respectively. In calculation of the functions, the disturbance conditions along six directions are given in a range of dimensionless translational velocities of \(-0.4<v_b, w_b<0.4\) with an interval of 0.1, and rotational velocities of \(-0.02<p_b, q_b, r_b<0.02\) with an interval of 0.005. We know that the aerodynamic forces and moments all show an approximately linear relationship with respect to the corresponding disturbances. We hereby represent the aerodynamic forces and moments approximately by introducing a linear function of the disturbances for the six DoFs, in the form of:

\[
F(t) = \sum_{n=0}^{10} (a_{n}\cos(n\omega t) + b_{n}\sin(n\omega t))
\]

where \(\omega\) is the reduced frequency, and \(a_{n}, b_{n}\) are Fourier series coefficients. The higher the harmonics \(h\) is, the better this function fits the original value. In the present study, it is found that a value of ten (\(h=10\)) is sufficient to reproduce all the waveforms of the CFD-based aerodynamic forces and moments. The first term of this equation represents the equilibrium condition while the others represent the six directional disturbance conditions, respectively.

Then the disturbance functions are embedded into the equations of motion (Eq. (2.1)) to solve the time-varying state variable under disturbance conditions. Note that this is an initial-value problem, in the sense that once the initial conditions are specified, a unique trajectory of the body can be obtained. Therefore, within the range of disturbances being given previously, we here show the results in the longitudinal motion under three disturbance conditions of \(u_0, w_0=\pm0.05\), and \(q_0=\pm0.005\), where \(u_0\), \(w_0\) and \(q_0\) represent the initial values, respectively.

3. Results

3.1 Three natural modes in linear study

By solving matrix A, we obtain a series of eigenvalues and eigenvectors as shown in Tables 1 and 2. Four eigenvalues \(\lambda_{1,2}, \lambda_3\) and \(\lambda_4\) yield with a pair of complex \(\lambda_{1,2}\) which have a common positive real part and two opposite imagine values. These four eigenvalues divide the disturbance motion into three natural modes: an unstable oscillatory motion according to the complex eigenvalues and two subsidence modes according to the real eigenvalues. Furthermore, the polar form of the eigenvectors can be expressed as displayed in Table 3, in which the magnitudes and phases of the disturbance quantities relative to each other are shown. Since eigenvectors are unique in direction but not in magnitude we have scaled them to make \(\delta \theta = 1\).
In the results, due to the unstable oscillatory mode, the hovering flight of the fruit fly is dynamically unstable. We note that, however, in the unstable oscillatory mode as shown in Table 3, $\delta w$ is much smaller than $\delta u$ and $\delta q$, which means that $\delta w$ shows less feature than $\delta u$ and $\delta q$ in the unstable mode. In the fast subsidence mode, the similar results are given in which $\delta u$ and $\delta q$ show more actively than $\delta w$. In the slow subsidence mode, $\delta w$ is obviously larger than $\delta u$ and $\delta q$, implying that $\delta w$ has more slow subsidence feature.

3.2 Time-varying feature of the state variables under disturbance conditions

In the nonlinear study, to obtain trimmed or exactly balanced equilibrium condition corresponding to a steady hovering state without any deviation, we further carried out an extended study to tune the initial time and obtained an appropriate initial time of $t_0 = 5.173$. Then three longitudinal disturbances of $u_0 = 0.05$ and $q_0 = 0.005$ are given based on the equilibrium condition.

### Table 1  Eigenvalues of the system matrix

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\lambda_1$</th>
<th>$\lambda_2$</th>
<th>$\lambda_3$</th>
<th>$\lambda_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstable oscillatory model</td>
<td>0.009±0.02i</td>
<td>-0.02</td>
<td>-0.0015</td>
<td></td>
</tr>
<tr>
<td>Fast subsidence</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slow subsidence</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2 Eigenvectors of the system matrix

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\delta u$</th>
<th>$\delta w$</th>
<th>$\delta q$</th>
<th>$\delta \theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstable oscillatory</td>
<td>0.032±0.05</td>
<td>-0.064</td>
<td>-0.172</td>
<td></td>
</tr>
<tr>
<td>Fast subsidence</td>
<td></td>
<td>-0.0035</td>
<td>-0.951</td>
<td></td>
</tr>
<tr>
<td>Slow subsidence</td>
<td></td>
<td>-0.00035</td>
<td>0.0004</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3 Magnitudes and phase angles of each of three eigenvectors

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\delta u$ phase angle</th>
<th>$\delta w$ phase angle</th>
<th>$\delta q$ phase angle</th>
<th>$\delta \theta$ phase angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstable oscillatory</td>
<td>0.06</td>
<td>3.2E-4</td>
<td>180°</td>
<td>180°</td>
</tr>
<tr>
<td>Fast subsidence</td>
<td>0.064</td>
<td>3.5E-4</td>
<td>0°</td>
<td>180°</td>
</tr>
<tr>
<td>Slow subsidence</td>
<td>0.67</td>
<td>3.7</td>
<td>0°</td>
<td>180°</td>
</tr>
</tbody>
</table>

In the results, due to the unstable oscillatory mode, the hovering flight of the fruit fly is dynamically unstable. We note that, however, in the unstable oscillatory mode as shown in Table 3, $\delta w$ is much smaller than $\delta u$ and $\delta q$, which means that $\delta w$ shows less feature than $\delta u$ and $\delta q$ in the unstable mode. In the fast subsidence mode, the similar results are given in which $\delta u$ and $\delta q$ show more actively than $\delta w$. In the slow subsidence mode, $\delta w$ is obviously larger than $\delta u$ and $\delta q$, implying that $\delta w$ has more slow subsidence feature.
hence a reduction in forward deviation.

3.2.2 Vertical disturbance

Three longitudinal state variables \((u_b, w_b, q_b)\) are plotted in Fig. 3 in terms of two vertical disturbances of \(w_0 = -0.05\) (dashed blue lines) and \(w_0 = 0.05\) (dot-dashed green lines). Apparently, the vertical disturbance conditions result in a relatively modest time variation in the three state variables. The slow convergence of \(w_b\) from the outset is consistent with the results in the linear study which suggests that \(w_b\) is the main variable in the slow subsidence mode. The angular velocity \((q_b)\), however, shows some pronounced asymmetry between the negative and positive disturbances, which correspond with the nose-down and nose-up pitching motions (Fig. 3c). The downward (negative) disturbance seems to contribute to the nose-down pitch rate and the upward disturbance to the nose-up pitch rate, respectively.

3.2.3 Pitch disturbance

Pitch disturbance in terms of \(q_0 = -0.005\) (dashed blue lines) and \(q_0 = 0.005\) (dot-dashed green lines) are shown in Fig. 4. In these two cases, the state variable \(u_b\) shows a gradual divergence initially but turns to converge after eleven beat cycles (Fig. 4a); \(w_b\) shows subtle oscillations, particularly under the nose-down disturbance (Fig. 4b); and \(q_b\) converges gradually to the equilibrium state until the 8\(^{th}\) beat cycle indicating a static stability but then turns over to the opposite direction and diverge with the pitch angle subsequently exceeding 90\(^\circ\) (Fig. 4c), i.e., an obvious dynamic instability which is also referred in the unstable oscillatory mode in the linear study. This is because that a nose-up pitch disturbance can induce a backward motion due to the body rotation, which, as observed in the case of \(u_0 = 0.05\) (Fig. 2), may lead to a backward deviation and hence induce a nose-down pitch motion.

Figure 2. (a-c) Time variations of state variables \((u_b, w_b, q_b)\) under initial conditions of \(u_0 = -0.05\) (dashed blue lines) and \(u_0 = 0.05\) (dashed dotted green lines) with \(v_0 = w_0 = p_0 = q_0 = r_0 = 0\) and \(t_0 = 5.17\).
4. Discussion

4.1 Longitudinal stability of hovering fruit fly

Unlike that observed in the linear study, the nonlinear method-based results obviously show that all the longitudinal disturbances apparently initially show some converging tendency to the equilibrium state. The mechanism of this phenomenon is not very clear but a considerable possibility may lie in the existence of a passive mechanism termed FCF (Flapping Counter Force) which was investigated by Cheng et al. (25). They suggested that the FCF is produced during body translation by symmetric flapping wings. They also concluded that FCF plays a key role in flight stability due to the passive damping coefficient. Note that in their studies, only a single directional motion was taken into
account and hence the coupling effect among the 6DoF motion was ignored. In the present study, however, it is found that interactions among the three state variables show highly nonlinear features, e.g. in the case of pitch disturbance of $q_0 = -0.005$, a nose-down motion induces a forward translation when converges to the equilibrium condition. However, the induced-forward velocity subsequently results in a nose-up pitch angular velocity according to the case of $u_0 = -0.05$, which leads to the instability eventually. Such nonlinear interactions play a key role in quantifying and evaluating the flight stability during flapping flight.

4.2 Time-varying feature of passive dynamic stability

The linear study estimates and provides qualitative explanation on the responses of state variables consisting of three natural modes. It should be noted, however, the time-invariant aerodynamic forces and moments used in calculating the aerodynamic derivatives are employed in terms of the period-averaged through a single wing beat cycle. Moreover, in this model an integrated disturbance motion is considered as a linear superposition of three natural modes and hence any possible nonlinear interactions among the state variables were artificially dropped out. Therefore the linear model is incapable to capture some possible nonlinear effects such as the time-varying feature of 6DoF flight dynamics of a freely flying insect. In order to quantify how such time-varying characteristics in terms of unsteady aerodynamics and flight dynamics affect the passive stability in free flight, we carried out an extended study by investigating four cases in which the six disturbances (including the lateral state variables not being shown in the present paper) are added at different timing initially: \( A \), pronation; \( B \), mid-downstroke; \( C \), supination; \( D \), mid-upstroke. Here we introduce a definition of losing body attitude to describe the situation when any of the body angles around three axes exceeds a range of $-90^\circ$~$90^\circ$ (pitch angle varies over a range of $0^\circ$~$90^\circ$). As illustrated in Fig. 5a, we use the numbers of flapping cycle to evaluate whether the fruit fly model is able to sustain a hovering flight before losing its body attitude. Our results indicate that, although the dynamic instability is observed in all the cases, the feature that how long the free flight can be sustained is obviously distinguished from each other. This implies that the time-variant feature may play a key role in the passive dynamic stability because it is more important that how long the free flight of an insect can be sustained without losing its body attitude before implementation of any active modulation and/or feedback controls.

4.3 How can a fruit fly sustain a steady hovering?

The results of both of the linear and nonlinear studies suggest that hovering fruit fly is unstable when suffering disturbance from environment. The state variables interact each other and divergence from the equilibrium condition. In general, however, a real fruit fly never lose its attitude or perform unstable even in gust. The reason is that it can make continuous adjustment to its wing kinematics in order to keep steady hovering. Thus, when and how a fruit fly adjusts its wing kinematics is the important problem to be tackled. During the latency, whether a fruit fly will lose its attitude before it can apply active control is the key point in our study. In the study of visual mediated feedback of fruit fly, \textit{Drosophila melanogaster}, Bender and Dickinson \(^{(12)}\) suggested that the latency of vision-to-motor responses ranges from 10 to 25 ms. Meanwhile, in the study of haltere mediated feedback, Trimarchi and Murphey \(^{(26)}\) suggested that the latency between haltere nerve stimulus and b1’s motor neuron in fruit fly is 2.1 ms~8.5 ms. These mean that, a fruit fly can give an active response when suffering disturbances after at least 2.1 ms. In order to examine how long the fruit fly model is capable to sustaining a free flight of hovering before losing its body attitude, we conducted an extended study of the passive dynamic stability under a wider range of the translational disturbances of 0.25m/s ~ 1m/s, and of the rotational disturbances of 462deg/s ~ 1850deg/s, respectively. The time lapse from the
outset of disturbances to the instance when the model begins to lose its body attitude is plotted in Fig. 5b in terms of the six state variables which is converted to be dimensional values here. The results indicate that a hovering fruit fly is capable to retrieve its body attitude at least within 4 ms with a disturbance of 1 m/s, which implies that a fruit fly, even if its hovering flight would be of any dynamic instability, should have sufficient time to perform any active mediation after the latency.

Figure 5. (a) Flapping cycles before a fruit fly loses its body attitude in four cases with different initial times: A, pronation; B, mid-downstroke; C, supination; D, mid-upstroke. (b) Time lapse from the outset of disturbances to the instance when a fruit fly begins to lose its body attitude under a wide range of disturbances.

5. Conclusions

This study offered two computational frameworks to analyze the flight dynamics and hence the passive dynamic stability of insect hovering. The linear study identified three natural modes including one unstable oscillatory mode, one fast subsidence mode and one slow subsidence mode. Due to the existence of the unstable mode, the longitudinal dynamic stability of hovering fruit fly is suggested to be unstable. On the other hand, the nonlinear study provided the time-varying feature of the state variables under three longitudinal disturbance conditions. The results suggested that all the disturbances had the tendency to converge to the equilibrium conditions at the beginning, while $q$ diverged to the opposite direction before losing its body attitude. In the $u$ and $w$ disturbance conditions, however, insect shows a pitching divergence due to the interaction between state variables. Therefore, both of the two methods suggest that fruit fly doesn’t have the inherent dynamic stability in the absence of active control. That is, in the disturbed motion, fruit fly using the same wing kinematics as in the equilibrium flight might not return to the equilibrium ‘automatically’. Therefore, the study on the active control seems required and essential especially in the development of MAVs. As both of the passive and active stability is available after latency, our study also provided a quantitative analysis for the future work. As a future task, it will be a challenging topic to quantify what parameters of the body and wing kinematics play important roles in dominating steering and maneuvering of insect flight and how they interact with each other and work in flight control.

Acknowledgement

We thank Toshiyuki Nakata and Masateru Maeda for helpful discussions and for their support of this work. This work is partly supported by the Grant-in-Aid for Scientific Research of No. 21360078 and No. 18100002, JSPS, Japan. NG is funded by a MEXT scholarship. HL is also funded by a CJSP scholarship.
References


